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Discovery of a new, third kHz QPO in 4U 1608–52, 4U 1728–34, and 4U 1636–53
Sidebands to the lower kHz QPO?

Peter G. Jonker[1], Mariano Méndez[1,2], Michiel van der Klis[1]

ABSTRACT

We report the discovery of a third kilohertz quasi–periodic oscillation (kHz QPO) in the power spectra of the low–mass X–ray binaries 4U 1608–52 (6.3σ), 4U 1728–34 (6.0σ), and 4U 1636–53 (3.7σ) which is present simultaneously with the previously–known kHz QPO pair. The new kHz QPO is found at a frequency that is 52.8±0.9 Hz, 64±2 Hz, 58.4±1.9 Hz higher than the frequency of the lower kHz QPO in 4U 1608–52, 4U 1728–34, and 4U 1636–53, respectively. The difference between the frequency of the new kHz QPO and the lower kHz QPO increased in 4U 1608–52 from 49.6±1.4 Hz to 53.9±0.5 Hz when the frequency of the lower kHz QPO increased from 672 Hz to 806 Hz. Simultaneously the difference between the frequency of the new kHz QPO and the upper kHz QPO increased by ~60 Hz, suggesting that the new kHz QPO is unrelated to the upper kHz QPO. In 4U 1636–53 a fourth, weaker, kHz QPO is simultaneously detected (3σ) at the same frequency separation below the lower kHz QPO, suggesting the new kHz QPOs are sidebands to the lower kHz QPO. We discuss the nature of this new kHz QPO and its implications on the models for the kHz QPOs.

Subject headings: accretion, accretion disks — stars: individual (4U 1608–52, 4U 1728–34, 4U 1636–53) — stars: neutron — X-rays: stars

1. Introduction

In the last four years observations with the *Rossi X–ray Timing Explorer* (RXTE) satellite have revealed the presence of several quasi–periodic phenomena at frequencies higher than 100 Hz in the Fourier power spectra of low–mass X–ray binaries (LMXBs). First, the kilohertz quasi–periodic oscillations (kHz QPOs) were discovered (van der Klis et al. 1996a,b; Strohmayer, Zhang, & Swank 1996; Strohmayer et al. 1996; for the most recent review see van der Klis 2000). Somewhat later, nearly coherent oscillations were discovered during type I X–ray bursts in several of these LMXBs

[1]Astronomical Institute "Anton Pannekoek", University of Amsterdam, and Center for High-Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam; peterj@astro.uva.nl, michiel@astro.uva.nl, mariano@astro.uva.nl

[2]Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina

(Strohmayer et al. 1996; for a review see Swank 2000); these burst oscillations presumably occur at frequencies close to the neutron star spin frequency (Strohmayer et al. 1996).

The kHz QPOs are nearly always found in pairs. Although their frequencies can vary over several hundred Hz, the frequency separation between the twin kHz QPOs, $\nu_2 - \nu_1$, remains approximately constant, close to the inferred spin frequency of the neutron star (but see e.g. van der Klis et al. 1997; Méndez et al. 1998a; Méndez, van der Klis, & van Paradijs 1998; Méndez & van der Klis 1999). Various models exist for the origin of these QPOs. Immediately after their discovery a beat frequency model was proposed (Strohmayer et al. 1996), of which the sonic–point model is the most elaborate example (Miller, Lamb, & Psaltis 1998). Later, Stella & Vietri (1998) proposed the relativistic precession model (see also Psaltis & Norman 2000; but see Marković & Lamb 2000) and Osherovich & Titarchuk (1999) introduced the two–oscillator model. In the latter model the QPO at ν_1 (the lower kHz QPO) occurs at the Keplerian frequency of material orbiting the neutron star, whereas in the other two models the QPO at ν_2 (the upper kHz QPO) is the one that is Keplerian.

The possibility that sidebands to the two main kHz peaks could occur was mentioned by several authors (Miller et al. 1998; Psaltis & Norman 2000; Miller 2000), but no sidebands, nor in fact any other kHz QPOs beyond the initial pair were detected up to now (see e.g., Méndez & van der Klis 2000). In the LMXBs 4U 1608–52, 4U 1728–34, and 4U 1636–53 the kHz QPOs have been extensively studied on previous occasions (4U 1608–52, Berger et al. 1996; Yu et al. 1997; Méndez et al. 1998a,b; 4U 1728–34, Strohmayer et al. 1996; Strohmayer, Zhang, & Swank 1996; Ford & van der Klis 1998; Méndez & van der Klis 1999; 4U 1636–53, Zhang et al. 1996; Wijnands et al. 1997; Méndez, van der Klis, & van Paradijs 1998; Kaaret et al. 1999, Méndez 2000).
In this Letter, we describe the discovery of a new, third kHz QPO close to the lower kHz QPO in these three sources, which is probably an upper sideband to the lower kHz QPO. We discuss briefly the possible implications of this discovery in terms of the existing models for the kHz QPOs.

2. Observations and analysis

We have used observations obtained with the proportional counter array (PCA; Jahoda et al. 1996) onboard the RXTE satellite (Bradt, Rothschild, & Swank 1993). The observations of 4U 1608–52 used here are the same as those described by Méndez et al. (1999, and references therein); the observations of 4U 1728–34 are those used by Strohmayer et al. (1996), Strohmayer, Zhang, & Swank (1996), Ford & van der Klis (1998), and Méndez & van der Klis (1999). The observations of 4U 1636–53 used in this paper are listed in Table 1.

We used data with a time resolution of at least 122μs to calculate power spectra of data segments of 64 s up to a Nyquist frequency of 4096 Hz in two different energy bands, from 2.0–8.7 keV and from 8.7–60 keV if available, and in one band combining the total effective PCA energy range (2.0–60 keV). Observation 10094-01-01-00 of 4U 1608–52 only covered the 2.0–13.2 keV band and we excluded it in the calculation of the fractional rms amplitudes of QPOs. We selected only those power spectra in which a narrow (full–width at half maximum, FWHM, less than $\sim$10 Hz) lower kHz QPO was observed. This resulted in $\sim$67, $\sim$92, and $\sim$80 ksec of data in the 2.0–60 keV range which corresponds to $\sim$18%, $\sim$12%, and $\sim$15% of the total amount of analyzed data for 4U 1608–52, 4U 1728–34, and 4U 1636–53, respectively.

We traced the lower kHz QPO using a dynamical power spectrum (e.g. see plate 1 in Berger et al. 1996) displaying consecutive power spectra to visualize the time evolution of the QPO frequency. For each source separately, we fitted this QPO peak in each power spectrum in the range 100 Hz above and 100 Hz below the traced QPO frequency (so to exclude the upper kHz QPO) with a constant plus a Lorentzian. For each source separately, we used the shift-and-add method described by Méndez et al. (1998b) to shift each lower kHz QPO peak to the same frequency and average the aligned power spectra. We then fitted each average power spectrum (one per source) with a constant plus Lorentzians to represent the QPOs. Errors on the fit parameters were calculated using $\Delta\chi^2 = 1.0$ (1σ single parameter). The 95% confidence upper limits were determined using $\Delta\chi^2 = 2.71$.

3. Results

Figure 1 shows the resulting power spectra for 4U 1608–52, 4U 1728–34, and 4U 1636–53 after applying the abovementioned procedure. We discovered a new kHz QPO in these three sources at a frequency that is, respectively, 52.8$\pm$0.9 Hz, 64$\pm$2 Hz, and 58.4$\pm$1.9 Hz higher than that of the lower kHz QPO, at a significance level of 6.3σ, 6.0σ, and 3.7σ (single trial), respectively (Table 2). This new kHz QPO is detected at the same time as the twin kHz QPOs that were already known in these sources.

In 4U 1636–53 we detected a fourth kHz QPO, at the same frequency separation below the lower kHz QPO (Figure 1, Table 2). This new kHz QPO was detected in a single trial, at a 3σ significance level. The presence of two, symmetrically located, peaks on either side of the lower kHz QPO suggests the new kHz QPOs are sidebands to the main peak and from now on we will refer to these new kHz QPOs as such. No significant lower sidebands could be detected in the other two sources.

We applied an F–test to the χ^2 of the fits with and without the upper sideband in order to test its significance. We derived values for the significance of the upper sideband similar to those calculated from the errors in the fit parameters which we quoted above. Conservatively estimating the number of trials involved in obtaining our results at $\sim$400 (the number of frequencies where we searched for a QPO, $\sim$4000, divided by the FWHM of the QPO $\sim$10 Hz) still results in a $> 5\sigma$ detection in case of 4U 1608–52.

For each source we divided the data into two parts based on the frequency of the lower kHz QPO in the power spectra. In each of these parts we shifted the lower kHz QPO peak to the same frequency as before and fitted the average power spectrum. In 4U 1636–53 and 4U 1728–34 the separation

Table 1. Log of the observations of 4U 1636–53 used in this analysis. For the observations we used in our analysis of the other sources see main text.

Observation ID	Date & Start time (UTC)
10088-01-01-00	27-04-1996 13:45
10088-01-02-00	29-04-1996 17:37
10088-01-03-00	30-04-1996 16:03
10088-01-07-01	09-11-1996 20:53
10088-01-08-03	31-12-1996 18:23
10088-01-06-01	06-01-1997 05:58
10088-01-06-07	06-01-1997 08:32
30053-02-01-000	24-02-1998 23:26
30053-02-01-001	25-02-1998 05:55
30053-02-02-02	19-08-1998 08:15
30053-02-02-01	19-08-1998 13:03
30053-02-01-01	20-08-1998 01:50
30053-02-01-02	20-08-1998 03:26

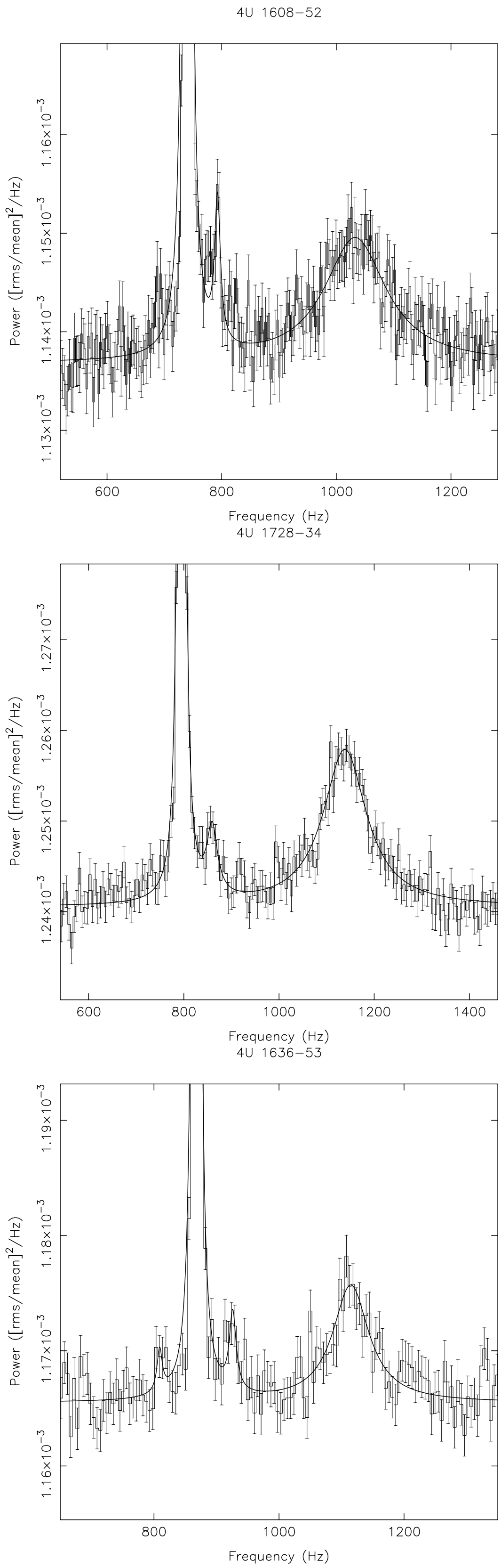

Fig. 1.— Power density spectra of the three sources showing the lower and upper kHz QPO and to the high frequency side of the lower kHz QPO the new QPO. The power is rms normalized after Belloni & Hasinger (1990). Note that due to the applied shift–and–add method, only the frequency difference with respect to the frequency to which the power spectra were shifted is meaningful (see also Table 2).

between the upper sideband and the main peak, Δ_{SB}, is consistent with being the same in the two parts, whereas in 4U 1608–52 Δ_{SB} increases significantly (2.9σ, Table 2). In 4U 1608–52, the frequency of the upper sideband increases by ∼139 Hz as the frequency of the lower kHz QPO increases by ∼134 Hz. The fact that the distance of the sideband remains approximately constant (to within ∼4.5 Hz) as both peaks move over ∼135 Hz is an additional argument supporting the interpretation of the new kHz QPO as a sideband to the lower kHz QPO. Simultaneously, the frequency distance of the sideband to the upper kHz QPO changes by nearly 60 Hz; this and the fact that the sideband is much narrower than the upper kHz QPO, strongly argues in favor of the sideband being un–related to the upper kHz QPO.

To correct for the relative motion of the sideband with respect to the main peak, which artificially broadened it in our previous analysis, we calculated the frequencies to which each power spectrum should be shifted in order to align the sideband, assuming a linear relation between the frequencies of the sideband and the main peak. Applying this new shift to the data of 4U 1608–52 we indeed obtained a narrower sideband (9.7±2.2 Hz), although the effect is marginal. Aligning the power spectra on a hypothetical lower sideband did not result in a significant detection in 4U 1608–52. The upper sideband is also significantly detected in 4U 1608–52 when only a fraction of the data is selected and no shift-and-add is applied, although at a smaller significance level.

Applying the same shifts to the power spectra calculated for the two energy bands, we measured the dependence of the fractional rms amplitude on photon energy of the detected QPOs. Only for 4U 1608–52 we were able to significantly detect the sideband in both energy bands. The increase in fractional rms amplitude with energy in 4U 1608–52 is different for the lower and upper kHz QPO (see Méndez et al. 1998b). Although the fractional rms amplitude of the sideband increased from 1.7%±0.2% to 2.6%±0.3% as a function of photon energy (2.0–8.7–20 kev) in 4U 1608–52, the uncertainties on the measurements of the fractional rms amplitudes of the sideband did not enable us to distinguish between the two different trends observed for the kHz QPO pair. The FWHM of the lower kHz QPO, that of the upper kHz QPO, and that of the sideband nor the sideband separation nor the peak separation between the upper and lower kHz QPO changed significantly with respect to the values obtained in the total energy band.

We also investigated the lower frequency part of the power spectra for the presence of a QPO at a frequency equal to the difference between the sideband and the lower kHz QPO. We detected a low frequency QPO (LFQPO) at 40.9±0.7 Hz with a FWHM of 19±2 Hz and a fractional rms amplitude of 2.8±0.1% in 4U 1608–52 (see also Psaltis, Belloni, & van der Klis 1999). In 4U 1728–34, a LFQPO at 41.5±0.2 Hz, with a FWHM of 19.9±0.8 Hz and a fractional rms amplitude of 5.3±0.1% was present (see also Ford et al. 1998; Di Salvo et al. 2000). In 4U 1636–53 no LFQPO was found, but a broad noise component was detected which could be described with an exponentially cutoff power law with a cut off frequency of 70±18 Hz, a power law index of 0.0±0.1, and a fractional rms amplitude of 2.8±0.1%.

4. Discussion

We have discovered a new kHz QPO at frequencies close to the frequency of the lower kHz QPO in the three LMXBs 4U 1608–52, 4U 1728–34, and 4U 1636–53. This new kHz QPO moves in frequency with the lower kHz QPO and maintains a distance to it which is nearly (but not exactly) constant; its distance to the upper kHz QPO varies much more. In 4U 1636–53 an additional QPO was found symmetrically located at the lower frequency side of the lower kHz QPO peak (3σ). These facts suggest that the new kHz QPOs are sidebands to the lower kHz QPO.

If these QPOs are sidebands due to an amplitude modulation of the lower kHz QPO, there must be an additional mechanism reducing the amplitude of the lower sideband or enhancing the upper sideband, since in 4U 1608–52 and 4U 1728–34 the presence of a symmetric lower sideband can be excluded. If the lower kHz QPO is a beaming oscillation, a single-sideband (rotational) beat frequency scenario could apply (e.g. Alpar & Shaham 1985). However, this would lead to a lower rather than an upper sideband, opposite to what is observed, unless the modulating part of the disk is counter rotating. When both rotational modulation and amplitude modulation of the formation of the lower kHz QPO produce sidebands, but of opposite phase, destructive interference could in principle cause the amplitude of the lower frequency sideband to be suppressed. Kommers et al. (1998) observed sidebands to the pulses of the pulsar 4U 1626–67 at much lower frequencies ($\sim$0.1Hz). There the lower sideband was stronger than the upper one and they proposed a model using both amplitude modulation and rotational modulation of the pulsar beam.

The frequency separation between the sideband and the main peak ($\sim$50–60 Hz), hereafter 'sideband separation' is reminiscent of typical frequencies of horizontal branch oscillations (HBOs) in Z sources and low frequency QPOs (LFQPOs) in atoll sources. However, the frequency of the LFQPO ($\sim$41 Hz) apparent in two of the three sources is inconsistent with the observed sideband separation. Furthermore, the increase in sideband separation with increasing lower kHz QPO frequency we observed in 4U 1608–52 is less than the increase in HBO frequency with lower kHz QPO frequency usually seen (Psaltis et al. 1999). So, the sidebands appear to be unrelated to the LFQPO in these atoll sources. Mechanisms that might explain these QPOs, such as the magnetospheric beat frequency model (Alpar & Shaham 1985; Lamb et al. 1985) or the Lense-Thirring precession model (Stella & Vietri 1998) could be used in explaining the LFQPO and the sideband, however one model can not explain both simultaneously unless the LFQPO and the sideband reflect frequencies at different radii in the disk.

None of the kHz QPO models in the literature (e.g. the sonic point model, Miller et al. 1998, Miller 2000, the relativistic precession model, Stella & Vietri 1998, and the two–oscillator model, Osherovich & Titarchuk 1999) in their present form predict the presence of an upper sideband to the lower kHz QPO with a sideband separation different from the LFQPO frequency.

One of the effects possibly occurring in the sonic point beat frequency model (Miller et al. 1998, Miller 2000) could perhaps explain the formation of the upper sideband we discovered. The density enhancements along the spiral flow responsible for the generation of the lower kHz QPO rotate around the neutron star ∼5–10 times before reaching the surface (Miller et al. 1998). Therefore, the orbital frequency of the enhancements is higher than the orbital frequency at the sonic point, the beat frequency will end up at slightly higher frequencies than the frequency of the lower kHz QPO. Since the sideband has a FWHM of ∼10 Hz corresponding to at least ∼100 cycles at a Keplerian frequency of 1000 Hz, the beat frequency will end up at frequencies 50–100 Hz higher. The orbital frequency of the enhancements and the change in the sideband separation as a function of the frequency of the lower kHz QPO, as observed in 4U 1608–52, will depend on the details of the physical processes at work close to the neutron star.

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Table 2. The properties (2.0–60 keV) of the lower (ν_1), upper (ν_2) kHz QPO peaks, and of the new kHz QPO (ν_{SB}) for 4U 1608–52, 4U 1728–34, and 4U 1636–53.

	4U 1608–52			4U 1728–34			4U 1636–53		
Parameter	∼67 ksec[d]	∼33 ksec[e]	∼34 ksec[e]	∼92 ksec[d]	∼42 ksec[e]	∼50 ksec[e]	∼80 ksec[d]	∼40 ksec[e]	∼39 ksec[e]
rms_1 (%)	8.47±0.02	8.66±0.03	8.89±0.02	6.71±0.02	6.56±0.04	6.99±0.03	6.66±0.02	7.30±0.02	5.98±0.03
FWHM_1 (Hz)	4.85±0.03	5.45±0.06	4.38±0.04	7.5±0.1	9.1±0.1	6.6±0.1	4.75±0.04	4.28±0.04	5.8±0.1
ν_1 (Hz)[a]	740	672	806	795	733	847	867.5	843	893
rms_2 (%)	5.1±0.2	6.2±0.2	4.0±0.2	5.5±0.1	6.1±0.1	4.9±0.3	3.3±0.2	3.7±0.2	3.1±0.2
FWHM_2 (Hz)	131±10	105±8	130±18	111±6	95±5	141±20	70±7	99±15	51±9
$\Delta\nu$ (Hz)[b]	293±3	308±3	253±6	343±2	350±2	324±5	247±3	260±5	242±3
rms_{SB} (%)	1.77±0.14	2.0±0.2	1.3±0.1	1.79±0.15	2.1±0.2	1.4±0.2	1.18±0.17	1.1±0.2	1.5±0.2
FWHM_{SB} (Hz)	12±3	15±4	5±2	27±7	38±10	15±6	13±6	10±3	27±10
Δ_{SB} (Hz)[c]	52.8±0.9	49.6±1.4	53.9±0.5	64±2	65±4	65±2	58.4±1.9	56.6±2.7	62.4±5.1
rms_{SB2} (%)[f]	<0.9	<1.2	<1.1	<1.3	<1.5	<0.9	0.8±0.2	1.0±0.1	<1.0

[a]Average frequency for the lower kHz QPO before shifting.

[b]Frequency separation, $\Delta\nu = \nu_2 - \nu_1$, between the upper and lower kHz QPO.

[c]Frequency separation, $\Delta_{SB} = \nu_{SB} - \nu_1$, between the upper sideband and the lower kHz QPO.

[d]Measurements for all available data

[e]Data were divided according to the frequency of the lower kHz QPO.

[f]95% confidence upper limits to the amplitude of the lower sideband were calculated by fixing the other parameters at the values obtained for the upper sideband.